THE ART AND SCIENCE OF MODERN FLIGHT TESTING - A PERSONAL VIEW

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ABSTRACT

Some examples of flight research undertaken by the RAE in the field of aerodynamics, stability and control, and handling are used to illustrate the view that this type of flight testing is still very much a mixture of art and science. The advances made in the capabilities of instrumentation, data recording and processing facilities are acknowledged but many of the chosen examples necessarily used very modest resources, yet succeeded in producing valuable results, often of wider significance than originally foreseen. The value of this type of flight test is partly in increasing confidence in predictions based on wind tunnel and simulator tests but in many instances the flight result is unique.

I. INTRODUCTION

If a dozen assorted aeronautical scientists and engineers were asked, individually, what the term "flight testing" meant to them, one would very likely end up with at least 12 different descriptions. Equally likely, the same enquiry directed at "wind tunnel testing" would produce a fair measure of agreement that this is a relatively exact science, conducted in fairly precise, controlled conditions, usually characterised by graphical plots of results through all the data points.

The reasons for this difference are obvious but still worth repeating. Flight testing concerns the entire real aircraft, in a real environment, with a human pilot who is an integral part of the system. The system's components embrace the entire range of disciplines that make up the science of aeronautics. Any one of these components may be the subject of a particular flight test but in general all the others have to function in the course of that flight and their behaviour may or may not interact with the prime subject of the test. Conditions are changing continuously - the weight is reducing as fuel is used; a different sample of the atmosphere is being traversed - and no single quantity can be chosen as an independent variable.

Small wonder, then, that the flight test fraternity tends to regard itself as a race apart - an elite corps who, with their test pilot colleagues, have some claim to be the source of the "real" information* on how the total system behaves. Their skill lies in devising experiments from which, despite imperfect control of test conditions, results may be obtained for comparison with predictions or for the formulation of new theories or the evaluation of new concepts.

There are two main classes of flight testing - research and development. The former is chosen as the main theme of this paper, for the simple reason that it is here that the author's experience exclusively lies. For the same reason, the areas of flight research chosen are concerned with aerodynamics, stability and control and handling.

There is an important distinction between flight testing for research and that for development. Development flying is part of the final essential step in clearing a new project for service. Basically it is aimed at showing that the aircraft and all its systems perform in the manner expected. With the high costs of flying today and the importance of time schedules, the general tendency is to play safe and record almost everything. Problems must be expected and one cannot afford to waste any opportunity to collect data that may assist in their solution. To put it crudely, the emphasis is on quantity rather than on quality. There is no point in measuring the performance or defining the behaviour to higher precision than will be available to the operator in routine service use of the aircraft. Of course performance specifications generally, have become more comprehensive and more precise and the standard of accuracy required in development flight testing is such as to leave no room for complacency among the flight test engineers involved.

It is research flying that has really set the standards of required accuracy, particularly when the objective is to collect data on the full-scale aircraft for comparison for example, with that from wind tunnel or other laboratory-type tests or from theory. This class of flight research has been the stimulus for significant advances in accuracy of transducers and for closer definition of their response characteristics. These advances, together with the ability to record and process automatically large quantities of data that has evolved to meet the growing needs of development flight testing, have given the flight research engineer such capabilities as were almost undreamed of in the early days of flight testing. In the author's view, the problem today is to make a sensible selection from the complex and sophisticated (and expensive) equipments that are available and avoid letting the tail wag the dog!

Not all flight research requires high precision of data recording. An important area in the context of this paper concerns the ability of the pilot to deal with the problems or uncertainties associated with new concepts (V/STOL, slender wings) or new operating procedures (steep approaches, direct lift control). Here, the primary data source is the pilot's report, backed by sufficient numerical data to describe the behaviour which the pilot is assessing. The essential experimental skill that is called upon here is to devise safe but productive flight tests that will illuminate the main problem areas and suggest profitable lines for further development and improvement.

II. FLIGHT RESEARCH IN THE RAE

The Royal Aircraft Establishment (RAE), with its major centres at Farnborough and Bedford, is the primary source of aeronautical research and development in the UK. Its disciplines are wide and cover the whole of the Air Systems requirements

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* "The aeroplane does do these things and if the theory does not give warranty for the practice, then it is the theory which is wrong" - John William Dunne, Farnborough, 1913.

of the UK Ministry of Defence. There are about 10 different Research and Development Departments, each subdivided into an average of 5 research divisions and it is the activities of one of these divisions that will be used to illustrate the role of flight research - the former Flight Division of Aerodynamics Department ("Aero Flight"), now known as the Flight Dynamics Division of Flight Systems Department. This Division was located at Farnborough from the early 1930s until it moved to Bedford in 1955/6. Figure 1 shows the airfield and the main building complex at Bedford.

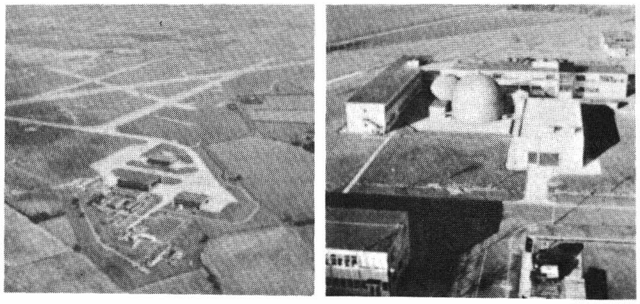


Figure 1 - Royal Aircraft Establishment, Bedford - General Views.

Most of the R & D departments in the RAE engage in flight testing in one form or another. In the author's Division, our research aircraft have always been our main experimental facilities, supported to an ever-increasing extent by piloted flight simulation. The role of the flight simulator will be touched on later when we consider the future of flight research. First, some examples will be given of the kind of flight research undertaken by this Division in the recent and not-so-recent past.

2.1 Early Studies of Carrier Deck-landing Problems

It will probably not be denied that the landing of any aircraft on the deck of a ship at sea makes the biggest demands on the pilot's skill and airmanship. Deck landing accidents in the Royal Navy during World War II, plus the growing importance of air power at sea, encouraged the creation of a special group within this Division to examine the piloting problem. One early step was to record a number of actual carrier-landing approach paths and the appropriate aircraft parameters (speed, engine setting, control usage, etc) to illustrate what was being demanded of the aircraft and the pilot. Then in consultation with these pilots, a draft set of low-speed flying qualities requirements was formulated, covering performance and controllability in the longitudinal and lateral/directional modes. Although they were written over 30 years ago (but not published (1) until 1951) these requirements are quite topical in concept because they define the response required in terms of what the pilot was trying to achieve rather than the more common definition of the modal characteristics of the dynamic behaviour. Some workers in the field of modern flying qualities requirements believe that this more direct form of response definition will eventually have to be adopted.

The flight test programme continued with the comparison of these draft requirements with the actual behaviour of 4 current naval aircraft - Seafire, Barracuda, Hellcat and Avenger. These example aircraft already had well-established reputations as good or bad deck-landing aircraft and the comparisons showed that generally about the right level had been set. As the reported results (1) of these tests show, there were problems with measuring some of the flightpath response characteristics, due to instrumentation limitations but with the help of the test pilots' assessments, a rational interpretation of the results was achieved. It is believed that the principle of comparing existing aircraft with new formulations of requirements is a sound one and could be more widely adopted.

That the introduction of the jet engine and the nose-wheel undercarriage overtook this particular piece of work is a fact of history but there were new problems requiring research. One early worry concerned the loss of slipstream lift from the propeller, believed to have been an important element in longitudinal control during deck-landing. One of the first naval jet aircraft - a Vampire - was therefore fitted with what amounted to a direct lift control (DLC) system in 1947. The wing flaps were driven, about a mid-position giving almost $\pm 0.15g$ on the approach, by signals from the engine throttle lever (rather than from the stick as on modern systems). Static and dynamic performance measurements were made and actual deck-landing trials were conducted. However, the poor mechanical design of the system - backlash, friction and "sponginess" - and the poor engine response clouded any benefits in approach path control and the scheme was dropped, not to re-appear for many years (in the mid-1960s). The history of DLC might have been different had we been able to get this scheme to work properly but the evolution of new deck-landing techniques removed the requirement.

The study of these techniques continued by the obvious and direct process of recording actual approach paths to define what was being done. Though the Royal Navy and the US Navy used different techniques, both involved major changes in the flightpath in the vertical plane in the final part of the approach. In neither case was the initial steady approach path aimed at the intended touchdown point, as shown in Figure 2.

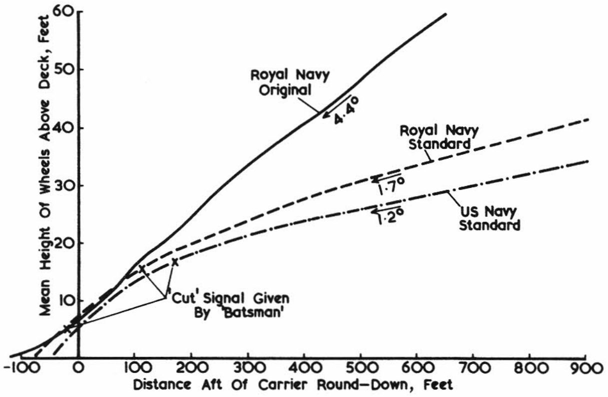


Figure 2 - Typical Deck-landing Approach Paths.

The need for these precise "last minute" manoeuvres and the lack of precise approach path guidance in the final stages of the landing were both eliminated by the elegantly-simple device that became known as the mirror landing aid. The original proposal was due to Commander (now Rear Admiral) H C N Goodhart RN and the system was developed by this Divison through several series of carrier trials at sea, to the point where it was adopted by both British and American navies with dramatic reductions in deck-landing accident rates. The contribution of the test pilots in ensuring acceptance of the new landing technique can scarcely be overemphasised. One message from this piece of work is surely that the best way to deal with a difficult manoeuvre is to eliminate the need for it.

A final example of how this early Naval flight research had wider implications concerns the development of a piloting technique for landing without undercarriage on a flexible deck. Viewed from this point in history, the whole concept of landing an aircraft without wheels on a rubber deck seems wildly impractical but, thanks to the enthusiastic cooperation of a team of dedicated test pilots, it was in fact shown to be entirely feasible. The major problem which virtually "killed" the scheme, concerned the removal of the aircraft from the rubber deck to allow the next aircraft to land.

For these pioneering flight tests, a single arrester wire spanned the deck at a height of about 3 feet and it was essential that the aircraft (Vampire) crossed it at low speed and in level flight, with a height tolerance of about ±1 foot. Prior to trials at sea, a deck was constructed on the airfield at Farnborough so that the technique could be practised. For the first attempt at an arrested landing on this deck, the pilot used a lower approach speed and descended to a very low height earlier than he had done before in "dummy runs". When he attempted cautiously to gain height (the arrester hook was trailing on the grass of the airfield) by backward movement of the stick, the aircraft rotated but did not climb. It hit the rigid end of the deck in a nose-up attitude so that it cleared the wire but the arrester hook bounced up and missed the wire. The aircraft came to rest on the grass ahead of the deck, somewhat damaged but the pilot was unhurt.

The outcome of this incident was the recognition, for the first time, of the importance of minimum drag speed as an approach criterion. Thereafter, the low speed drag polars of every available aircraft were obtained by flight test (2) and tentative criteria were established for minimum acceptable approach speeds. The theory of stability under constraint was later put on a rigorous footing by Neumark (3), but it had not appeared as a problem as far as is known until the incident described above.

2.2 Flight Testing of Aircraft With Powered Lift

With the Harrier now in service with the RAF and the USMC, it may be of interest to recall the part played by flight research in this exploitation of the powered lift concept.

In 1952, the uses of jet lift to improve landing performance were being studied enthusiastically though the ultimate goal of VTOL still required major engine developments. To gain first hand experience of the engineering, aerodynamic and handling problems of building and operating an aircraft whose engine thrust could be deflected in flight, a Meteor twin-engined fighter was modified (Figure 3).

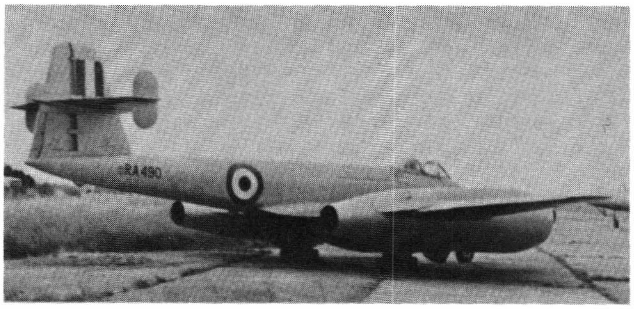


Figure 3 - Meteor Aircraft with Jet Deflection

The Derwent engines were replaced by more powerful Nenes and moved forward of the wing so that when the jets were deflected via butterfly valves in the new bifurcated jet pipes, the 60 degree deflected thrust line still passed near the centre of gravity. The normal thrust line was unchanged as was the control system.

These were two research areas of interest. The first concerned the piloting problem of approach path control with jets deflected. At full power the vertical component of thrust was over 50% of the aircraft weight. The normal power-off stall speed was 98 knots and the lowest indicated airspeed ever reached was 65 knots, though control became inadequate below about 75 knots. In this condition total thrust required was increasing as speed was reduced and the strong cross-coupline of longitudinal and normal forces made the correction of height and speed errors very difficult. The fixed jet deflection angle exaggerated the problem.

The second research topic concerned the aerodynamic interaction between the deflected jet and wing flows. To investigate this, the engine thrust had to be measured in flight using fixed rakes across the exit nozzle. Some evidence was found (4) of a lift loss, though the accuracy must be doubtful in view of the extremely asymmetric flow conditions in the nozzle.

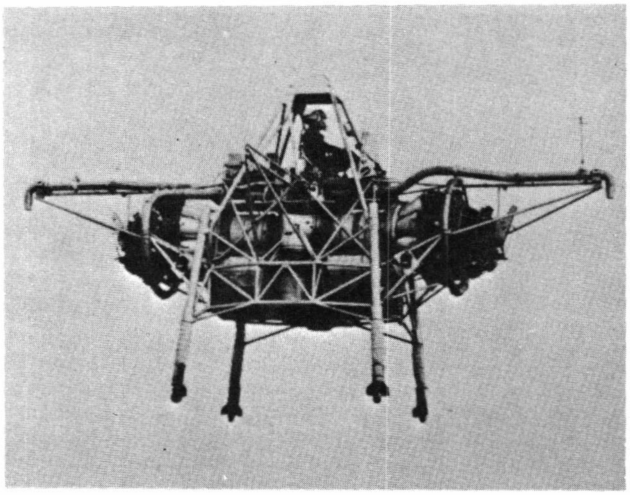


Figure 4 Rolls Royce "Flying Bedstead"

This flight experiment was soon overshadowed by the arrival of the first of the UK's VTOL research vehicles - "Flying Bedstead" (Figure 4) - which made its first flight in August 1953. This was the essential first step in the realisation of an operational VTOL aircraft, since it had to tackle the problem of control and handling at the hover. Laboratory tests with a remotely controlled model had shown that stability augmentation would be essential and the "Bedstead" had a duplex full authority electrically-signalled system with a third, passive monitor channel providing damping and some stiffness via "leaky integrator" circuits, in pitch and roll. Its control powers were too low and control lags were too large to allow any systematic variation but it could be manoeuvred quite precisely at low speeds and at least we had some lower limits to acceptable control characteristics.

This experience was fed into the design of the control system for the Short SCI research aircraft (Figure 5), which was the first to perform a complete transition from vertical take-off to conventional flight and back again to a vertical landing (at Bedford on 6 April 1960). This aircraft had 4 Rolls Royce RB 108 light-weight lift engines which could be tilted bodily fore and aft by ±23 degrees for horizontal acceleration control and a fifth RB 108 for propulsion. Its autostabiliser was triplex, electrically-signalled, with 40% more authority than that available to the pilot, to avoid saturation at full control input. Over a 10 year period, the autostabiliser was developed substantially (5) and display systems for low visibility operations were evaluated. Almost all the test flying concentrated on these aspects and by correlating the test pilots' opinions with detailed measurement of the control and response characteristics of the aircraft, the results could be translated into generalised design criteria and were incorporated, for example, in the recommendations for flying qualities requirements produced by AGARD (6).

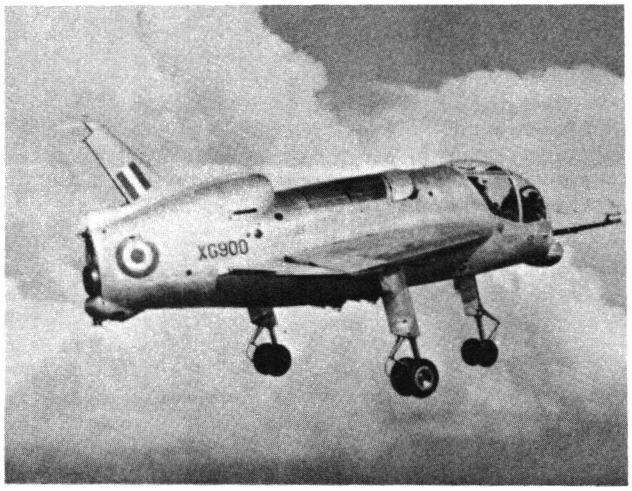


Figure 5 - Short SCI V/STOL Research Aircraft.

The major new piloting problem requiring investigation concerned the control of thrust vector angle during the decelerating transition. The pilot in effect, now had three variables (pitch attitude, engine thrust and vector angle) to control the two approach parameters of speed and flightpath angle. Fortunately, the Division's flight simulator facility was, by this time, able to contribute to a solution of the problem of redundant control. In a systematic series of tests in which the pilots had far more time to assess various techniques than they had on the short-duration research aircraft, it became clear that the pitch attitude could be held more or less constant with the stick, while lift thrust and vector angle were varied to control flightpath angle and deceleration respectively.

In retrospect, it is somewhat surprising that the lessons learned on the jet-deflection Meteor did not seem more relevant to the problem with the SCI and that the benefit of a controllable vector angle was not more readily apparent.

During the course of the research flying with the SCI, the view was formed that autostabilisation, at least to the extent of artificial damping of the pitch and roll response modes, would be essential for an operational aircraft. Our experience with the "Bedstead" and the SCI, plus accumulating US experience, showed that without this facility precise hovering was very difficult. The Hawker Siddeley Aviation Company were then developing the P-1127 aircraft (later to become the Harrier) and were most anxious to avoid the complication of autostabilisation. Their early hover tests (started in October 1960) were performed in this condition and to our initial surprise, their pilots and ours found very little difficulty. Eventually it was recognised that, given adequate control power and a well engineered control system with no lags or backlash, the pilots could indeed cope. We later found the same result on the SCI when, instead of merely switching off the rate feedback term in the control system (but retaining electrical signalling), we changed to the (emergency) direct manual control system. What at one time seemed like a conflict of opinion was eventually satisfactorily resolved by careful flight test and could not have been resolved in any other way. Today, the Harrier is fitted with a simplex 3 axis autostabiliser since all agree that this makes the control of the aircraft easier and safer but it is known that the aircraft can be controlled satisfactorily with any one of these axes unstabilised in the event of a failure.

Practically the whole of our flight test programme on the SCI was devoted to the problems of stability and control during the transition and hover. There were problems of an aerodynamic nature associated with interference between the lift engine and wing flows, particularly in ground effect, but these were treated as problems to be lived with rather than the subject of detailed research studies. The main reason for this attitude was that the separate lift and propulsion engine configuration seemed less likely to be developed than the vectored thrust engine configuration of the P-1127/Harrier. Therefore, our aerodynamic studies of these phenomena were postponed until the prototype P-1127 aircraft became available for research (Figure 6).

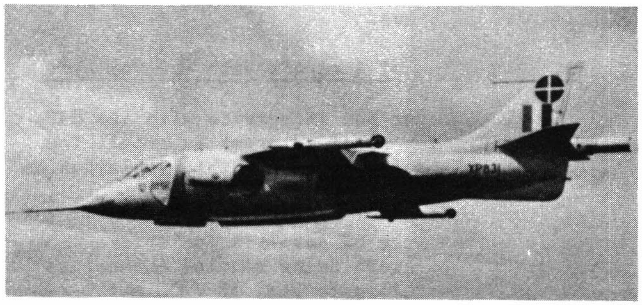


Figure 6 - Hawker Siddeley P-1127 Prototype.

Detailed tunnel tests had been made on a model of this aircraft but the representation of engine flows and the corrections for tunnel constraints were areas of uncertainty. Flight tests (7) have been made on the P-1127 to provide for the first time, data for direct correlation so that the confidence that may be placed in tunnel measurements may be assessed.

Whereas the earlier tests on the jet deflection Meteor only showed that there was a measurable lift loss and there were no tunnel tests for comparison anyway, these tests on the P-1127 were much more ambitious and had the complication of a further variable, thrust vector angle. New non-steady flight test techniques were devised to reduce the flight time involved but as a result, the data analysis has proved a difficult problem. Today a digital magnetic tape system would have been used, allowing fully automatic data processing but on the P-1127 we had to use analogue trace recorders. This data has now all been digitised and analysis is proceeding but, in retrospect it may be questioned whether we chose the right compromise between the more economical non-steady flight technique with a massive data analysis burden and the simpler partial glide technique, requiring more flying but less effort in the analysis.

This is not an isolated problem, nor has it been fully resolved. In the author's view, a flight research division with only limited resources probably needs to be somewhat conservative in its attitude to using the full capacity of modern data collection and processing techniques and should hang on to the well tried procedures until the necessary new support facilities are available and have been demonstrated.

2.3 Flight Research With Slender Wing Aircraft

The performance benefits of the slender wing were evident early in the development of the Concorde but were accompanied by serious doubts about the lateral stability and control of this configuration at the relatively high angle of attack that would be required for landing. Free-flight model tests were enthusiastically undertaken by the flight dynamics experts at Farnborough and several people narrowly escaped injury from the many paper-dart-shaped models that were being hand-launched around the office building! These light-hearted activities had a serious purpose and an encouraging outcome, in that the angle of attack limit for the dutch roll instability seemed to be higher (around 15 degrees) than early tunnel tests had predicted. Later tunnel tests still showed that the lateral/directional handling characteristics would be seriously deficient by existing standards. To resolve these doubts, the Handley Page HP 115 (Figure 7) was built. It was a small (20 ft span) pure delta shape with 75 degrees leading edge sweep. The initial flight tests were nautrally approached with caution but in the event the aircraft proved docile and even pleasant to fly. The dutch roll instability settled into a limit cycle oscillation at angles of attack above about 20 degrees and could be stopped immediately by forward movement of the stick. The aircraft was actually barrel-rolled in one practice demonstration at Bedford, although discretion suggested that this manoeuvre was not required of Concorde and it was not repeated in public.

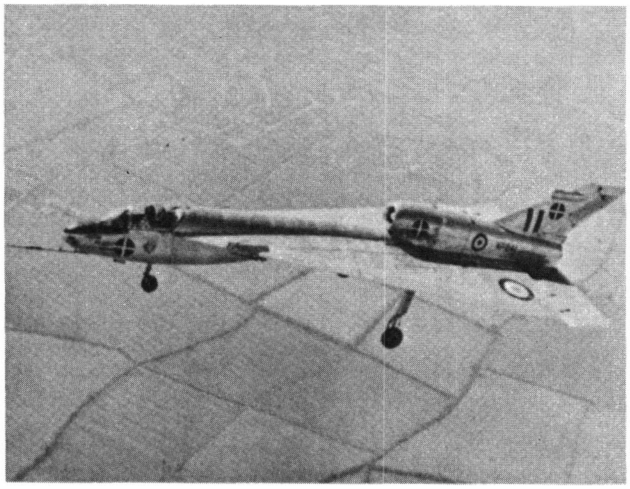


Figure 7 - HP 115 Slender Delta Research Aircraft.

Systematic flight tests (8,9) were undertaken in which most of the lateral/directional and longitudinal stability and control derivatives were measured for comparison with tunnel data. A variety of static, quasi-static and dynamic flight test techniques were used, including the applied-moment technique. An example of the comparison in respect of rudder power is shown in Figure 8. Longitudinally, the analysis was a more complex problem because of substantial nonlinearities in lift and pitching moment with angle of attack, etc but all the dynamic characteristics have now been extensively analysed (10) by modern parameter identification techniques.

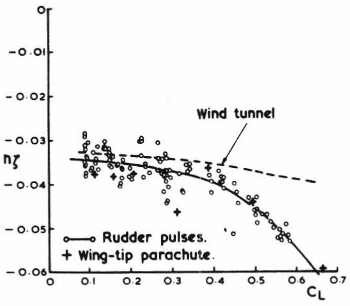


Figure 8 - Rudder Power Measurements on HP 115.

It is worth noting that the wealth of data produced by this interesting aircraft was obtained by use of only two 8-channel analogue trace recorders. It is regarded in this Division as a classic example of modern research flight testing, even though the recording system was "old fashioned." On a cost-effectiveness basis, it is doubtful whether it could have been improved upon.

The other slender wing research aircraft used by the Division was the BAC 221 (Figure 9), developed from the one-time world absolute speed record holding aircraft, the Fairey FD-2. This was rebuilt with an ogee wing plan form and was close to a one-third scale model of Concorde. A comprehensive flight test programme was undertaken to provide aerodynamic data for comparison with that from tunnels, with the speed range extended up to M=1.65. Particular attention was paid of course, to the transonic region. Not only were performance, stability and control studies made, but extensive measurements were made of the steady and fluctuating pressures on the wing to help validate wing structural design criteria.

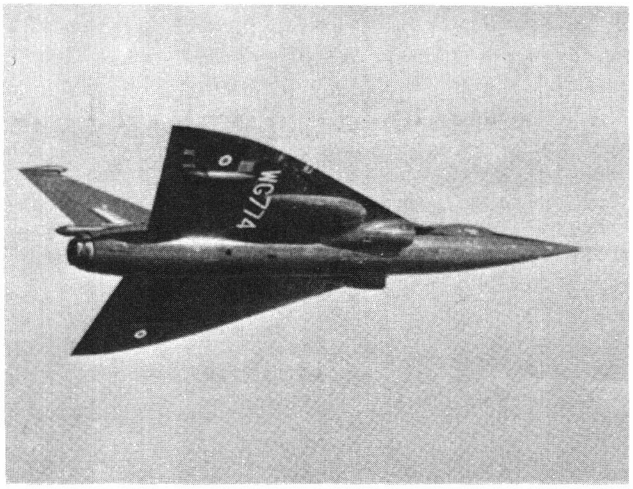


Figure 9 – BAC 221 Research Aircraft.

Two particular handling phenomena were encountered and studied for the first time on this aircraft. A sideslip divergence was found when the wings were held level with aileron at an angle of attack where the static weathercock stability was still positive. Theoretical analysis (11) of the dynamics of flight with bank angle constrained subsequently showed a loss of stability depending on the ratio of yawing to rolling moment produced by the ailerons. Secondly, this aircraft was operationally limited by its zero rate of climb speed – a concept already recognised as a possible airworthiness criterion. On the BAC 221, it was possible for the first time to examine this limiting flight condition and techniques for recovery from it. Both this aircraft and the HP 115 were invaluable not only as pure research aircraft but equally as forms of insurance against unexpected handling problems on Concorde itself.

2.4 Full-scale Aerodynamic Flight Research

All the predictions of the performance and behaviour of a new aircraft are put to the test during development flying. When shortcomings are revealed, specific solutions are sought but once the procuring authority is satisfied, these tests can be concluded. There is seldom the opportunity for a systematic analytical study of the detailed differences between prediction and actuality.

One of the purposes of the research flight tests conducted by this Division is the provision, in selected cases, of flight data of a quality and form that can be compared directly with wind tunnel data. Almost all of the special research aircraft that we have used have been tested in this way since they all embodied novel aerodynamic features, the extrapolation of whose characteristics from model test data to fullscale was inevitably in some doubt. This could not be done on a wholesale basis of course but was concentrated on these features – mainly the stability derivatives – which defined the handling characteristics and which were of prime interest to this particular group of handling specialists. The tests on the HP 115 already mentioned, illustrate this philosophy. More recent flight tests (10) concerned with the manoeuvring limits of combat aircraft have used a standard Gnat trainer (Figure 10) and have involved specific tunnel tests to provide the necessary basis for correlation. It is only by conducting systematic tests and attempting detailed correlations that the confidence to be placed on predictions can be properly assessed and improved.

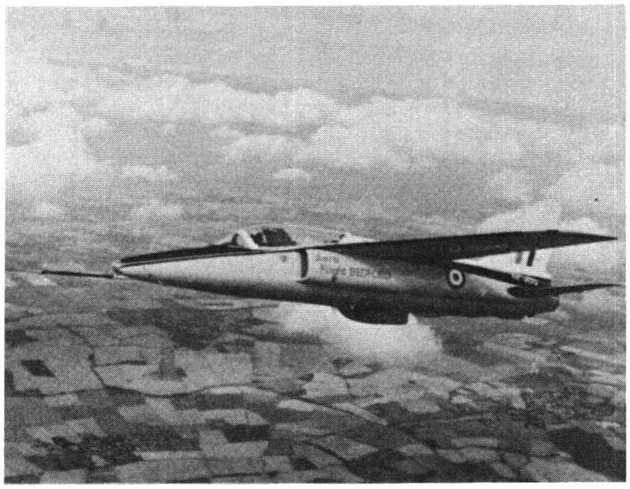


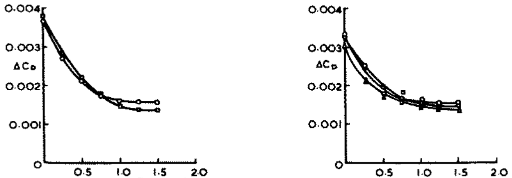
Figure 10 – Standard "Gnat" Trainer Used for Research.

Considerable ingenuity has to be exercised in devising flight tests in this category since in the general case, every stability derivative has some effect on the disturbed dynamic motion of the aircraft. Modern parameter identification techniques are capable of analysing such motions and are more frequently used today, with substantial economies in flight test time. In practice, the flight test procedure is to try to excite only those modes whose controlling derivatives are of prime interest and extract these from the analysis, accepting that the derived values of derivatives which do not have much effect on those modes may be widely in error.

While the capabilities of these new techniques are already impressive and will continue to improve, there may yet be a place for the simple, elegant flight test that can give immediately credible results. Two examples will illustrate the point:

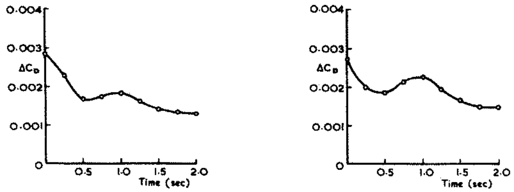
(a) Aileron and rudder powers on the HP 115 were measured, inter alia, by the "applied moment" technique. For the rudder power derivative, a small parachute was streamed from one wing tip to produce a measurable yawing moment input. When this parachute was released after the test, a well-defined yawing transient occurred which was analysed (12) to yield a value for the yaw inertia that agreed within 2% with the value measured in ground rig tests. Yaw acceleration had to be measured with linear accelerometers mounted fore and aft of the centre of gravity, since no suitable angular acceleration transducer was available. The method has potential for small, structurally stiff aircraft and in principle could be applied to other axes, for example by releasing weights from the wing tips or rear fuselage.

(b) A method for measuring the incremental drag of wing-mounted stores was developed (13), based on analysis of the transient response of the aircraft following store release. One result was the evidence of a favourable interference effect (Figure 11), resulting in the lowest aircraft drag when the store was just released from but was still close to the pylon. A more intriguing result occurred when, instead of conventional 1000 lb inert bombs, empty fuel tanks were dropped. The normal acceleration record showed a large positive transient (over 1.8g total) as the tanks tumbled away. Naturally the flight data was suspected but check calibrations revealed no serious error. The effect was repeated on a later flight and some simple tunnel tests were therefore arranged with model tanks suspended free of the aircraft, in positions determined from cine film records of the release behaviour in flight. To everyone's surprise, lift increments on the model of the same order as those found in flight were recorded. Though largely of academic interest, this result illustrates the fact that the flight environment is the only one that reproduces all the correct conditions and unexpected results cannot be dismissed simply because they have not previously been observed in the wind tunnel.



a. 250kt M=0.41

b. 300kt M=0.50



c. 350kt M=0.58

d. 400kt M=0.66

Figure 11 - Incremental drag changes following store release.

III. THE FUTURE OF FLIGHT RESEARCH

In the specialised context of this paper, two things have happened which influence the climate under which flight research is undertaken today. On the one hand, wind tunnel techniques and facilities have developed considerably and because of the extensive tunnel/flight correlations that have already been made, the confidence in predictions based on their results is generally high. On the other hand, the flight simulator has benefitted from even more significant developments and today its protagonists claim that practically all of the handling problems that have occupied the attention of the handling, stability and control experts in the past can now be investigated on the research simulator. Of course the confidence with which this assertion is made is based on experience of validating simulator assessments by direct comparison with flight experience.

In both cases therefore, flight research has contributed to the value of these ground-based facilities and has never been in competition with them. Special research aircraft have been built and tested - the RAE had eight such aircraft in the period 1950-1970 - whenever a new concept has been of such novelty that existing ground-based facilities could not provide answers to critical problems. We know now that the behaviour of these research aircraft can be predicted from wind tunnels and flight simulator results because we have made the comparisons but the era of the research aircraft can only be said to have ended if it is assumed that no entirely new concept in aerodynamics or propulsion will ever again emerge.

Flight research today and for the future is likely to be concerned with standard or modified production aircraft and with so-called "demonstrators". The latter class have, in a sense, replaced the research aircraft and relatively few surprises should emerge in the course of their flight evaluation which approximates to a development flying programme.

Flight research, even when conducted on standard aircraft, tends by its very nature to result in open-ended programmes. For example the Gnat (Figure 10) was originally acquired for a brief study of buffet onset in transonic manoeuvres for comparison with data on wing-root bending moment measurements from tunnel models. The flight tests revealed that deterioration in lateral/directional handling was at least as significant in determining these manoeuvring limitations. Fortunately it was possible to expand and extend the flight test programme to follow this new line and although the programme has now lasted much longer than originally forecast, the results have amply justified the extra cost and effort. The value of the flexible approach to management of such programmes is amply demonstrated.

The technology of flight testing has advanced enormously and in terms of data handling at least, is more than adequate to meet the needs of the flight research specialist. However, the more conservative practitioners sometimes feel a certain isolation from their experiments because of the variety of stages through which the raw data is passed before it appears as a computed result. The processes of signal conditioning, filtering, sampling, analogue-digital conversion, re-formatting and automatic data processing have introduced a number of other specialists on whose skill one must now rely. The more links there are in any chain, the more chance there is of a failure and the flight test engineer still needs to have at least an intuitive feeling of what his final results should look like.

In the field of transducers great advances have also been made, especially in the measurement of pressure, acceleration, linear and angular displacements and rates, etc. A valuable review of the whole state of the art is provided (14) by the series of AGARDographs produced by the Flight Mechanics Panel of AGARD.

However, not all requirements can be met off the shelf and a flight research organisation needs the capability of producing specialised equipments, for example, in the area of airflow direction, not only for angles of attack and sideslip but also for detailed fluid motion studies in support of wing aerodynamics research.

Finally, because in much of the research covered by this brief review the human pilot is as much the subject of study as the aircraft itself, we would welcome a consistent, reliable and meaningful way of measuring pilot workload. Some progress is being made (15) in the interpretation of pilots' heart rate but a lot more work will be needed before this - or any other physiological measure - can be accepted as replacing the wellknown Cooper-Harper Pilot Rating Scale. In the author's view, the skilled dedicated test pilot will remain an essential member of the research team, in this field at least. Flight research, almost by definition, involves exploration of the unknown. If we knew what to expect, we could arrange to measure or record it but without such foresight, we still need first to rely on the test pilot to identify and interpret any unexpected phenomenon affecting control or handling. Flight simulation has opened the door to new areas of study in this field but the special skills of the test pilot are as much required here as in actual flying.

VI. CONCLUDING REMARKS

Flight testing in the research context illustrated in this paper, is a challenging, rewarding and - in the author's experience - a frankly enjoyable activity. Over the period covered by this somewhat random choice of examples, the technology has advanced enormously, both in terms of hardware available and in techniques for its efficient use. The costs associated with flight testing are such as to encourage the collection of the maximum amount of data per flight hour. In this situation reliance on digital techniques and automatic data processing is almost inevitable. There is no doubt that this capability has made possible the production of flight research data of a type that was hitherto impossible. The work of Brotherhood (16) in measuring pressure distibutions on helicopter blades in flight is a classic example of the proper exploitation of available data handling facilities in a small research organisation.

Nevertheless, situations may still arise where instead of setting out to record every possible relevant parameter, it may be better to get a "feel" for the problem first, to record only a limited amount of data but sufficient to define the more profitable lines of detailed study. Without wishing to make a virtue of necessity, most of the examples used in this paper used very limited data recording facilities and generally proceeded in a stage by stage fashion, giving time and opportunity to assess and digest what had been learned en-route and to re-direct the programme as necessary.

This is perhaps the point at which to recall the given title of this paper - "the art and science of modern flight testing." No attempt has been made to give an up-to-date review of the techniques and equipments available, if only because it requires a whole series of AGARDographs (14) for example to do the subject justice. Nevertheless, it is hoped that the examples chosen will illustrate the view that flight research depends very much on a mixture of art and science, that the need continues to "expect the unexpected" and that the impressive capabilities of modern data acquisition and processing facilities must be kept firmly in their place as the servants, never as the masters, of the flight test engineer. We must not let the computers do our thinking for us.

V. ACKNOWLEDGEMENTS

The examples chosen to illustrate this paper have been drawn almost exclusively from the activities of one Division of the RAE. While the author is naturally proud to have been associated with a flight test team of such calibre, and gratefully acknowledges their contributions and help, it would be wrong to imply that this organisation is unique, or that the skills commended here are not available elsewhere. Flight testing is a worldwide activity and a close affinity and mutual respect exists among those engaged in it. A different author would have chosen different examples but it is believed the same conclusions could have been reached.

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